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Abstract

The present experimental study examines the performance of a novel fuel injector/burner configuration with respect to reduction in nitrogen oxide NO_x emissions. The lobed injector/burner is a device in which very rapid initial mixing of reactants can occur through strong streamwise vorticity generation, producing high fluid mechanical strain rates which can delay ignition and thus prevent the formation of stoichiometric diffusion flames. Further downstream of the rapid mixing region, this flowfield produces a reduced effective strain rate, thus allowing ignition to occur in a premixed mode, where it is possible for combustion to take place under locally lean conditions, potentially reducing NO_x emissions from the burner. The present experiments compare NO/NO₂/NO_x emissions from a lobed fuel injector configuration with emissions from a straight fuel injector to determine the net effect of streamwise vorticity generation. Preliminary results show that the lobed injector geometry can produce lean premixed flame structures, while for comparable flow conditions, a straight fuel injector geometry produces much longer, sooting diffusion flames or slightly rich premixed flames. NO_x measurements show that emissions from a lobed fuel injector/burner can be made significantly lower than from a straight fuel injector under comparable flow conditions.

Introduction

The necessity to progressively reduce the production of nitrogen oxides in aircraft combustion processes arises both from legislated and anticipated environmental standards and from the need to meet public environmental concerns. Because NO_x formation rates in general are strongly temperature dependent, it becomes effectively prohibitive for the combustion of fuel to take place near its stoichiometric mixture ratio, a fact that may render nonpremixed combustion inappropriate because of the diffusion flames that are prevalent[1-5]. The capability to mix fuel and air very rapidly relieves this problem to some extent[3, 6]; with rapid mixing the formation of stoichiometric diffusion flames is discouraged in favor of premixed flames, which can be made locally lean or locally rich and thus reduce NO_x

emissions[5, 8]. The rapid mixing principle is, in fact, the basis of two low NO_x burners proposed for the High Speed Civil Transport (HSCT) turbofan engine under supersonic flight conditions[7]. Partial premixing of fuel and air can reduce NO emissions due to a reduction in flame temperature and reduction in species residence times[4, 6], but emissions can also increase with partial premixing due to reduced radiative heat loss, which effectively increases flame temperatures[6]. Thus there appear to exist optimal levels of partial premixedness for which NO_x emissions (as well as emissions of CO and other species) can be minimized, as recently shown by Gore and Zhan[8].

The rapid mixing rates required to accomplish overall NO_x reduction in combustors almost invariably necessitate pressure losses in both the fuel and air streams, which may present an undesirable consumption of pumping power. Moreover, ultra high pressure ratio engines (60:1 or greater) with turbine inlet temperatures around 3000°F , proposed for the Advanced Subsonic Transport Aircraft, could necessitate combustor equivalence ratios which are relatively high (approaching stoichiometric). Thus, rapid mixing could become essential in advanced aircraft in order to meet emissions goals.

The fundamental goal of the present research program is to examine the combustion performance of a novel fuel injector/burner which has the potential for significant reduction in nitrogen oxide emissions when compared with conventional aircraft burners. The lobed fuel injector, shown schematically in Figure 1, is a device in which very rapid initial mixing of reactants can occur through streamwise vorticity generation[9], producing high strain rates which can delay ignition[10-13]. This streamwise vorticity is created by oppositely oriented secondary flows which develop along the sides of each of the lobes; these flows roll up into counter-rotating vortical structures oriented in the streamwise direction. Further downstream of the development of the vortical structures, the strain field relaxes, producing a reduced effective strain rate and potentially allowing ignition to occur in a premixed or partially premixed mode, where it is possible for combustion to take place under locally lean conditions. This rapid premixing before ignition may potentially reduce NO_x emissions from the burner under specific critical conditions.

The general principle of the lobed or louvred geometry has been applied to two-stream mixing in turbofan engines using a single corrugated plate or interface to mix initially separated fluids[14-21]. Strong secondary velocities are observed near the exit plane of the lobed mixer, which evolve into a sheet of streamwise vorticity and eventually coalesce into distinct streamwise counter-rotating vortices[18]. Further downstream, turbulent breakdown of the streamwise vortices occurs, the location of which is dependent on the ratio of streamwise velocities on either side of the mixer. Vortex breakdown is seen by Eckerle *et al.*[18] to be the critical phenomenon that significantly enhances turbulent mixing due to the generation of smaller scale turbulence at breakdown. Yet Yu *et al.*[21] find that enhanced mixing can actually occur upstream of the region in which vortex breakdown occurs, due to the localized, rapid production of turbulent kinetic energy.

Combustion in a lobed mixer geometry, with fuel and oxidizer initially separated by a single lobed splitter plate, has also been studied to a limited extent[22-24]. When using a lobed splitter plate the flame spread angle is double that created by a flat splitter plate,

indicating enhanced mixing processes and an increased rate of flame propagation[22]. Mixing rate augmentation due to the addition of streamwise vorticity was found to be less sensitive to the detrimental effects of heat release than the mixing rate for a planar shear layer configuration[24].

For combustor applications, the lobed injector (Figure 1) reported in the present paper has several potential advantages over the lobed mixer. First, for stoichiometries which require greater proportions of air than of fuel (as with typical hydrocarbon fuels), the lobed injector allows large flow area differences between fuel and air without loss of symmetry or mixing effectiveness of the lobes. Second, because in the lobed injector fuel is injected directly into the region of highest strain rates and greatest vorticity, all of the fuel is mixed with oxidizer in a rapidly straining flow field, so that mixing may occur under conditions near flame extinction or ignition delay. Third, when a thin “strip” of fuel is sandwiched between the oxidizer, ignition delay can occur at smaller strain rates than when fuel and oxidizer meet at only one independently igniting interface[25]; hence ignition delay could be easier to achieve in a lobed injector rather than a lobed mixer geometry. The lobed injector also has an advantage over other types of strongly mixed nonpremixed combustors in that energy losses and pressure drop are small, while mixing takes place over a comparatively short distance[17].

Recent mixing studies for the non-reactive lobed injector flowfield by our group indicate significant increases in mixedness and scalar dissipation or strain rates over a planar geometry[26]. These studies employ planar laser-induced fluorescence (PLIF) imaging of seeded acetone to generate spanwise mixture fraction images at various locations downstream of the injector; from these images, local unmixedness[27] and average scalar dissipation rates are determined, from which strain rates may be estimated (after Bish and Dahm[28]). The mixing studies show that strain rates can be created in the farfield of the injector that exceed those required for ignition prevention; this implies that strain rates in the near field of the injector could be even higher, potentially able to delay ignition during rapid mixing. Yet the mixing studies also show that, depending on the specific lobed geometry, the mixing and strain field characteristics may be altered substantially for a given injector for different flow conditions. The purpose of the present work is to examine the behavior of the lobed injector under combustion conditions, specifically monitoring NO_x emissions from the device to demonstrate its potential for mixing enhancement and emissions reduction.

Experimental Facility and Methods

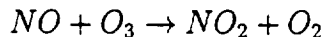
In the present experiments, two different planar fuel injector geometries were studied in a low speed combustion tunnel. The tunnel’s square test section had 9.5 cm sides; a schematic of the combustion tunnel is shown in Figure 2. A compressor was used to pass air through the combustion tunnel at speeds between 2 and 7 m/s in the test section. The tunnel entrance contained a honeycomb section to straighten the flow, followed by a contraction section of 4:1 area ratio. Quartz windows were fitted in the two vertical side walls of the test section and at the downstream end of the wind tunnel (in a plane perpendicular to the

bulk flow) for optical access. Movable rearward-facing steps were used in the combustion tunnel as flameholders; these steps were placed flush with the upper and lower walls of the test section and were oriented perpendicularly with respect to the fuel injector. The design of the flameholders was such that the rearward-facing steps could only be brought to within 6 cm of the fuel injector.

Two different fuel injectors were studied in this combustion tunnel; exit plane geometries are shown schematically in Figure 3. Propane fuel was used in all experiments described here. The **lobed injector A** was constructed of aluminum using an electron discharge machining (EDM) device. It was constructed of two plates which were planar and parallel at the upstream edge and sinusoidally corrugated (lobed) at the downstream edge. The plates were separated by a small gap (on average, 0.071 cm at the downstream exit plane) through which fuel surrogate flowed; the wall thickness at the exit was approximately 0.038 cm. It should be noted that, due to machining inaccuracies, the gap width and wall thickness of this injector did vary along the exit plane lobes. Both thicknesses became more than twice the nominal value at the peaks and troughs of the sine wave. The wavelength λ of the lobes was 1.905 cm, and the peak-to-peak amplitude at the exit was 3.721 cm. The injector had five lobes and spanned the width of the wind tunnel; it was 15.2 cm in length (in the direction of flow), so that the lobes grew at a constant ramp half-angle of approximately 7° . **Fuel injector B** was a straight slot injector with a slot width of 0.056 cm and with a wall thickness of 0.127 cm at the exit plane. There was no aerodynamic loading for injector B, and hence the principal mechanism for streamwise vorticity generation was removed. We examined this configuration in an attempt to isolate the effects of the lobes' streamwise vorticity generation on mixing from the effects of spanwise vorticity generation arising from the Kelvin-Helmholtz instability (when the upper and lower air flow velocities were unequal) and from the wakes caused by the finite thickness of the injector walls. The comparison of injectors A and B here is analogous to the comparison of a "petal" shaped fuel injector[29] with a circular fuel injector.

The two fuel injectors were each tested in the combustion tunnel for different sets of operating conditions. In the experiments described here, the axial velocities of the air streams (above and below the injector) were matched, where the fuel exit velocity was varied to produce different overall equivalence ratios for the tunnel. It should be noted that the overall equivalence ratio actually has little bearing on the injector performance since the local reaction takes place under *local* stoichiometric conditions; depending on the degree of entrainment of species, local stoichiometric conditions could be vastly different from global conditions.

A chemiluminescent NO – NO_x analyzer (Thermo Environmental 10AR Chemiluminescent NO – NO_x Gas Analyzer) was used to measure the NO and NO₂ emissions from the combustor. The analyzer generated ozone (O₃) and then mixed it with the sampled gases in a reaction chamber. As a result of the decay of electronically excited NO₂ molecules produced in the reaction



a chemiluminescent signal was obtained and monitored through a filter by a high sensitivity photomultiplier tube (PMT). The output of the photomultiplier tube was linearly proportional to the NO concentration. In order to help minimize calibration drift, a two point calibration was performed at each combustor operating condition where NO_x emissions were measured. A gas cylinder of certified 99.999% N₂ was used as the zero gas and a gas cylinder of 19.2 ppm NO in He from Matheson Gas Products was used as the calibrating gas. NO₂ emissions were measured by thermally converting NO₂ into NO (prior to the reaction with O₃) then determining the difference between the strength of this PMT signal and the NO measurement which had no thermal conversion.

The probe from the NO_x analyzer was placed well into the exhaust, downstream of the flame zones. Standard normalization of the NO and NO₂ emissions was made per kg of fuel burned on a dry basis. The emissions index of NO_x was then assumed to be equal to the sum of those for NO and for NO₂ made in the emissions measurements. In the near future, planar laser-induced fluorescence (PLIF) imaging of OH in the reaction zone will also be performed in order to better quantify reactive processes in the flame zone.

Results

Preliminary results from the present combustion experiments show dramatic differences in the visual structure of the flames formed in the combustion tunnel. For identical flow conditions (bulk air speeds and equivalence ratios), the lobed injector flames were bright blue in color, spanning the entire width of the flameholders, indicating the presence of lean premixed flames. The flames associated with the straight injector consisted of two distinct diffusion flame sheets, spreading toward the walls to become yellow further downstream. Even the visible flame characteristics indicated a substantial degree of mixing of fuel and air downstream of the lobed fuel injector, creating locally lean premixed or partially premixed flame structures. No substantial fuel-air mixing is observable within the test section for the straight injector; the flames themselves exist well into the plenum and occasionally into the exhaust section of the combustion tunnel.

Figure 4 shows plots of the emission indices for NO, NO₂, and NO_x as a function of overall equivalence ratio for both injectors under low speed conditions. Again, the overall equivalence ratio ϕ was based on the mass flow rates of fuel and air that were introduced into the tunnel; ϕ actually had little relevance to the *local* stoichiometry of the flame structures that form since *local* ignition can potentially take place in diffusion flame, lean premixed, or rich premixed flame modes. Results in Figure 4 demonstrate that the lobed fuel injector could actually produce lower emissions of NO and overall NO_x than could a straight (non-lobed) fuel injector under equivalent conditions. At the same overall equivalence ratio, NO emissions from the lobed injector were substantially lower than from the straight injector, indicating a much greater degree of mixing of the fuel with air and, locally, a much leaner reaction. An overall equivalence ratio just above 0.5 appeared to produce a maximum in NO production for the lobed injector; this indicated that the *local* equivalence ratio associated with the strained flame structures was likely close to unity at this condition. NO emissions dropped

with decreasing overall ϕ for the straight injector as well, indicating that this reaction may have been slightly premixed, but the magnitude of the emissions index indicated that this premixing was not substantial.

As overall equivalence ratio was reduced in Figure 4 for the lobed injector, NO_2 production peaked and then dropped, while for the straight injector NO_2 increased monotonically. Assuming that NO_2 formed due to the reaction of NO with oxygen-containing species near the flame and in the post-flame regions, it appeared that the $\phi \approx 0.4$ condition may have maximized entrainment of air into the flame/mixing zones for the lobed injector, thus forming higher NO_2 concentrations. On the other hand, air entrainment into the flame zone simply continued to increase in the straight injector with a higher air/fuel velocity ratio, leading to a peak in NO_2 at lower values of ϕ . The nature of NO_2 production demonstrates the sensitivity of the fuel injector/burner system to the evolution of the mixing field and the specific tailoring of the emissions production that is possible with the lobed injector.

It should be noted that equivalent values of the "overall ϕ " for the two injectors do not mean equivalent injectant/air velocity ratios. In fact, at the lower overall ϕ conditions (ϕ near 0.35), the ratio of fuel to air velocity for the lobed injector A is approximately 1.0, while the ratio for the straight injector is about 2.5. At the highest overall ϕ conditions (ϕ near 0.6), the ratio of fuel to air velocity for the lobed injector A is approximately 1.5, while the ratio for the straight injector is about 4.0. Hence the local fluid mechanics of the mixing process, in particular the generation of spanwise vorticity, is unequal between the two injectors despite having the same overall equivalence ratio.

Figure 5 shows the emissions indices as a function of overall ϕ for the lobed fuel injector, with two different bulk air speeds. Interestingly, the emissions indices for all three species are nearly the same as a function of ϕ . While the strain field and degree of mixing may increase as the air speed increases from 4.8 m/s to 6.0 m/s, any additional mixing did not appear to have a significant effect on NO_x emissions. These two different conditions may also represent the self-similar regions of the flowfield, which could explain the similarities in the emissions characteristics.

Figure 6 shows emissions indices for the lobed injector under the same (higher speed) operating conditions but where the flame holder was moved from a position 6.0 cm downstream of the injector to a position 14.0 cm downstream. As the flameholder was moved downstream, the emissions curves actually seemed to shift to the right, indicating the greater degree of fuel-air mixing that appeared to take place further downstream. As more air was entrained into the fuel-air mixture with downstream distance, the mixture became more lean; hence when ignition occurred at the downstream flameholder, it was in a leaner premixed mode for the lobed injector. This condition also had the effect of slightly increasing NO_2 production, since the greater degree of air entrainment increased the NO_2 formed from NO . Nevertheless, at given operating conditions (i.e., flow conditions and overall ϕ), the lobed injector flowfield demonstrated an increased degree of mixing downstream, and hence a lowered rate of NO emissions.

Conclusions

The present experiments confirm the usefulness of the lobed fuel injector concept as a means of NO_x emission reduction. For locally lean conditions, rapid fuel-air mixing by the lobed injector flowfield can cause lean premixed flame structures to ignite downstream, thus reducing flame temperatures and simultaneously reducing NO emissions. The alteration in the degree of local air entrainment by the lobed injector can also be used to maximize NO₂ production. Future work on this device will include investigation of combustion characteristics associated with an alternative lobed fuel injector (studied also in [26]) and detailed interrogation of the flowfield via laser diagnostics.

Acknowledgements

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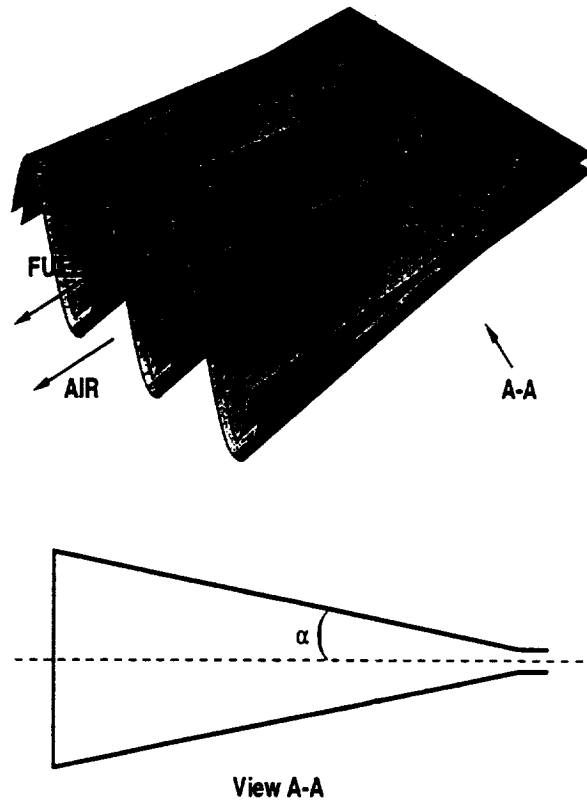


Figure 1. Schematic of the general lobed injector geometry.

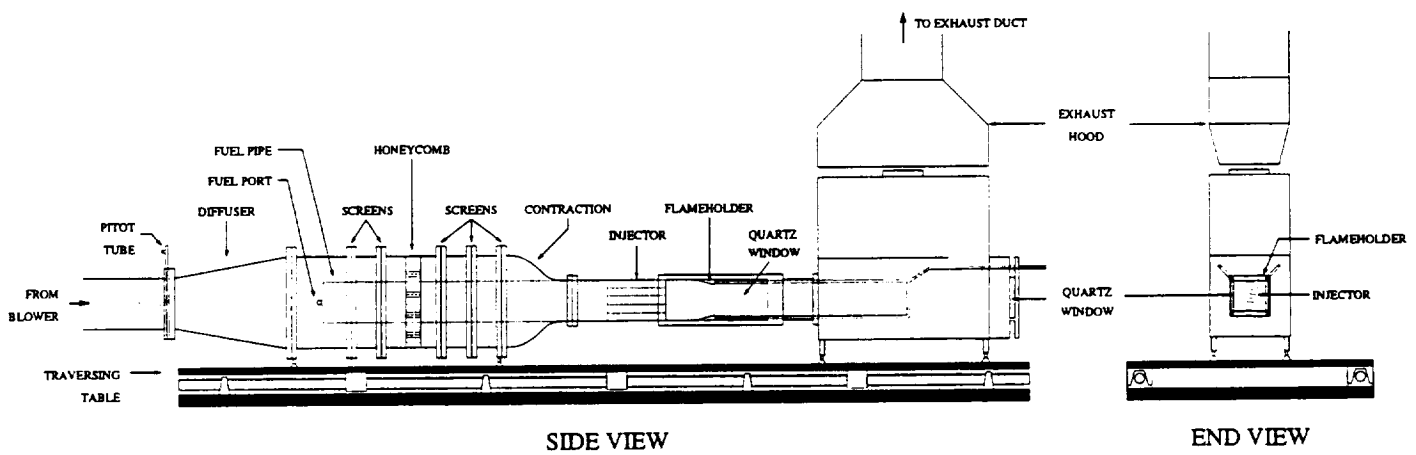


Figure 2. Schematic diagram of the combustor tunnel and experimental apparatus.

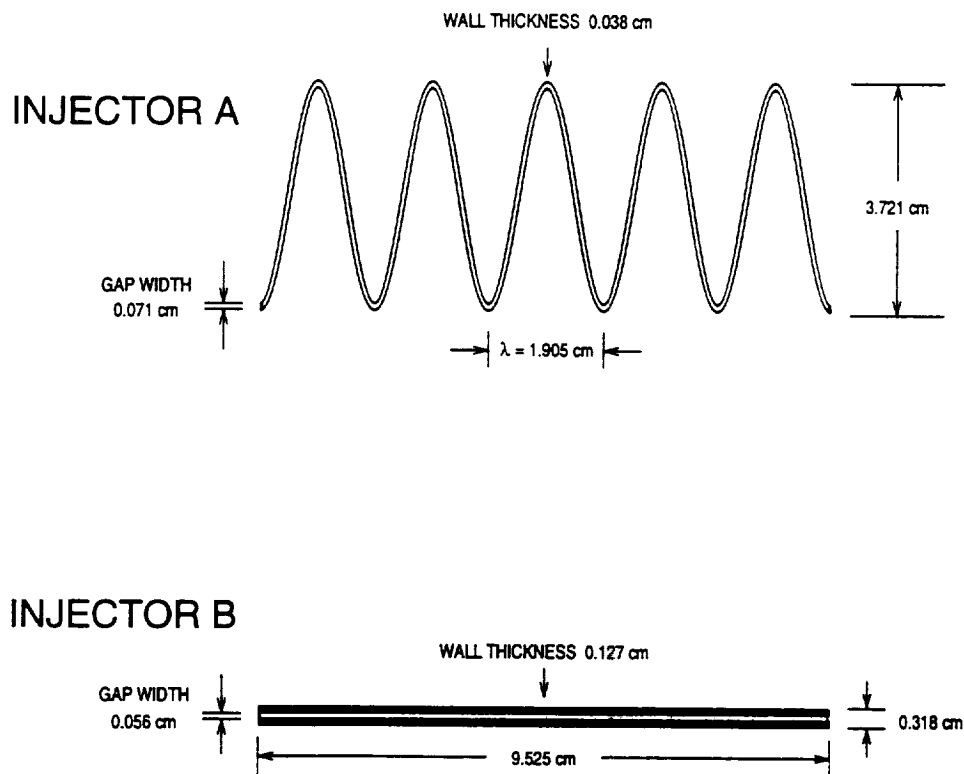


Figure 3. Comparison of exit plane geometries for the two injectors examined in the present combustion experiments: lobed fuel injector A and straight fuel injector B.

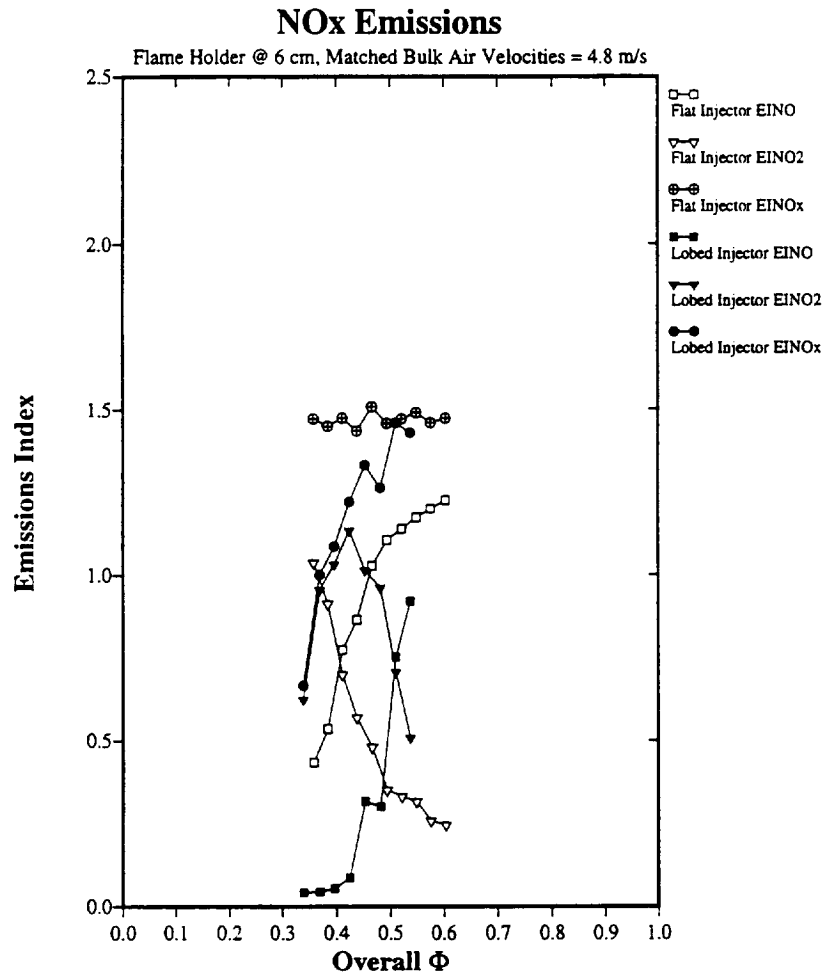


Figure 4. Emissions indices for NO, NO₂, and NO_x for the lobed fuel injector (A) and the straight fuel injector (B) as a function of tunnel overall equivalence ratio. The flameholder is situated 6.0 cm downstream of the injector, and the matched bulk air speeds are 4.8 m/s.

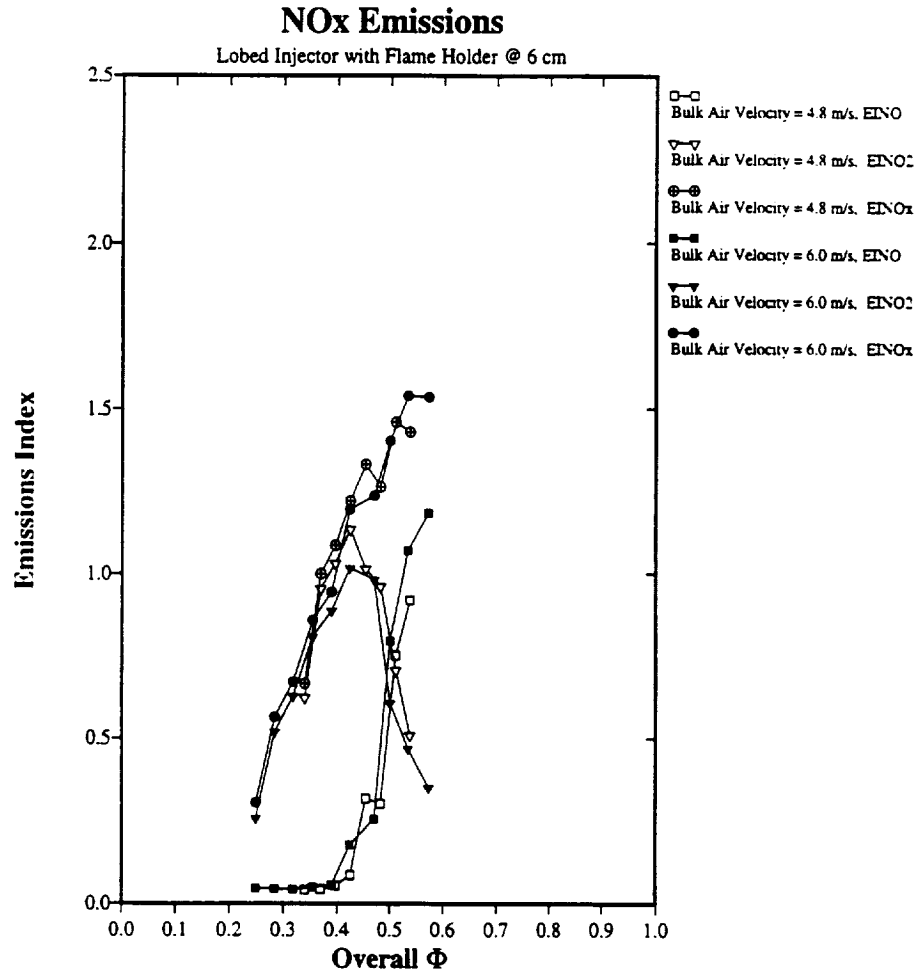


Figure 5. Emissions indices for NO, NO₂, and NO_x for the lobed fuel injector (A) as a function of tunnel overall equivalence ratio for two different matched bulk air speeds: 4.8 m/s and 6.0 m/s. The flameholder is situated 6.0 cm downstream of the injector.

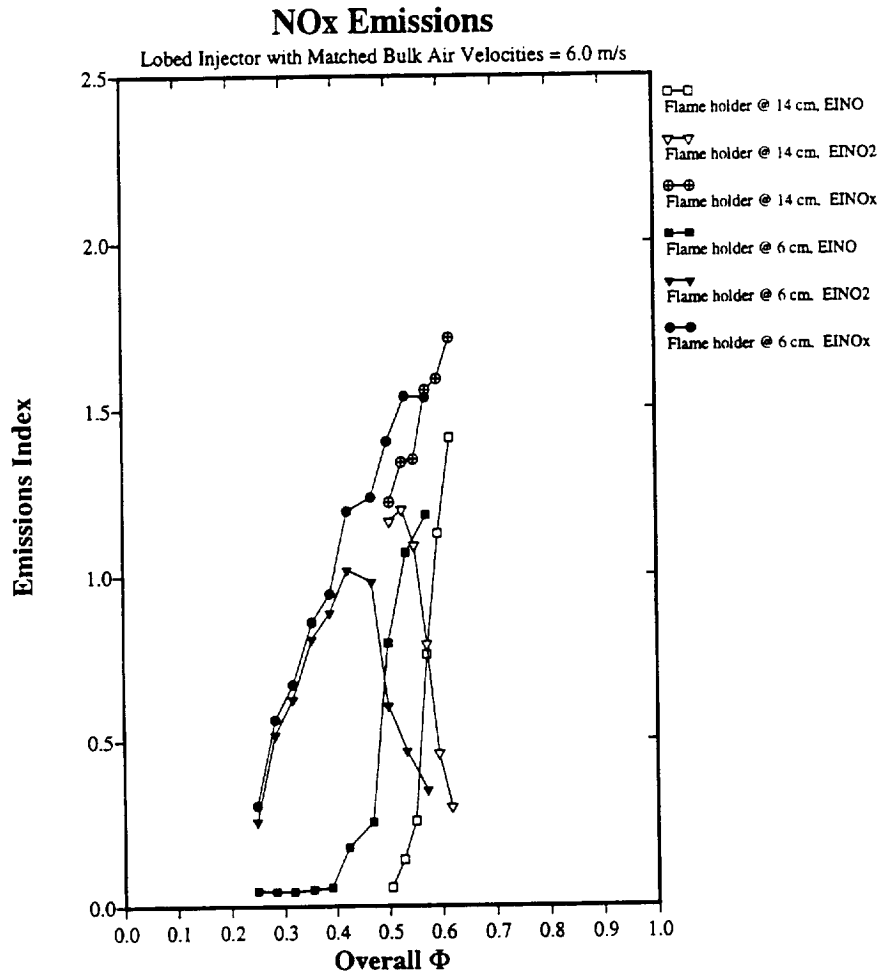


Figure 6. Emissions indices for NO, NO₂, and NO_x for the lobed fuel injector (A) as a function of tunnel overall equivalence ratio for two different locations of the flameholder: 6.0 cm and 14.0 cm downstream of the injector. The bulk air speed is 6.0 m/s.

